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MILLIMETER-WAVE IMAGING RADIOMETER (MIR) DATA PROCESSING
AND DEVELOPMENT OF WATER VAPOR RETRIEVAL ALGORITHMS

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ABSTRACT

This document describes the progress of the task of the Millimeter-wave Imaging Radiometer (MIR) data processing and the development of water vapor retrieval algorithms, for the second six-month performing period. Aircraft MIR data from two 1995 field experiments were collected and processed with a revised data processing software.

Two revised versions of water vapor retrieval algorithm were developed, one for the execution of retrieval on a supercomputer platform, and one for using pressure as the vertical coordinate. Two implementations of incorporating products from other sensors into the water vapor retrieval system, one from the Special Sensor Microwave Imager (SSM/I), the other from the High-resolution Interferometer Sounder (HIS).

Water vapor retrievals were performed for both airborne MIR data and spaceborne SSM/T-2 data, during field experiments of TOGA/COARE, CAMEX-I, and CAMEX-II. The climatology of water vapor during TOGA/COARE was examined by SSM/T-2 soundings and conventional rawinsonde.

1. INTRODUCTION

For study of atmospheric water vapor, cloud and precipitation, the microwave sensor is one of the major instruments for the investigation of these hydrological parameters. Water vapor profiling from space provides the much needed temporal and spatial coverages for this important meteorological variable. Both infrared (IR) and microwave techniques can be employed for this purpose, however, the latter is capable of penetration through thin clouds and provides the necessary information even when clouds are present.

Currently, the spaceborne humidity profiler, SSM/T-2 on board of the USAF polar orbiter, is operational and providing global water vapor information. A similar instrument, the Microwave Humidity Sounder (MHS) will be deployed into the future NOAA operational satellites for routine monitoring of global water vapor.

Airborne MIR, designed to have similar water vapor channels as the spaceborne sensors, was flown in NASA's field experiments of TOGA/COARE, CAMEX-I, and CAMEX-II. Its scientific objectives during the experiments include water vapor profiling, study of precipitation-related microwave signatures and validation of the SSM/T-2 sensor.

As more scientific field experiments are carried out and more radiometric data are collected, the objective of this task includes:

- i) Data processing, calibration, and image display of the acquired MIR data.
- ii) Development and improvement of the water vapor retrieval system for the humidity sounder.

In Chapter 2, newly acquired MIR data from various flight missions and their processing are described. Chapter 3 describes new developments of retrieval algorithm on a pressure coordinate system, and on a supercomputer platform for global retrieval algorithm. The incorporation of products from instruments of SSM/I and HIS into the system are discussed as well. Chapter 4 describes water vapor retrievals for the 1993 TOGA/COARE and CAMEX-I, and for the 1995 CAMEX-II as well. Recommendations for future research will be given in Chapter 5.

2. MICROWAVE DATA ACQUISITION AND PROCESSING

a) MIR Data from Alaska Field Experiment and of the Convection and Atmospheric Moisture Experiment (CAMEX-II)

Millimeter-wave Imaging Radiometer data were collected during two recent field campaigns of 1995. The first one was associated with snow and ice observation over Alaska and the Bering Sea area, where eight flights of MIR observation were made from April 3 to April 25, 1995. The second mission was associated with CAMEX-II over the eastern coast of the United States, where fifteen flights of MIR measurement were taken during August 23 through September 27, 1995.

The first set of MIR data has the usual measurements in six channels (89, 150, 183 ± 1 , 183 ± 3 , 183 ± 7 , and 220 GHz) and have been processed with the previous calibration and filtering procedures. MIR on the CAMEX-II flights, however, is a nine-channel radiometer, that is, the original six channels plus three additional channels at 325 ± 1 , 325 ± 3 , and 325 ± 8 GHz. The data processing software has been modified to include these additional channels. Besides, a triangular time-filtering function is used to replace the previous upstream nine-point running-mean averaging procedure. An independent set of calibration coefficients derived from a laboratory simulation are also used for the study and improvement of the MIR data calibration.

b) Global Data of Special Sensor Microwave Imager (SSM/I)

For purpose of inter-comparison and validation of water vapor retrievals from different microwave instruments, a set of the seven-channel SSM/I brightness data in different polarizations has been acquired from the Hydrological Sciences Branch, Laboratory for Hydrospheric Processes, Goddard Space Flight Center, NASA. These data are arranged in global maps with half by half degree grid system. They correspond to time period of Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE). These data will be used to derive total precipitable water, surface wind speed and liquid water content that in turn can be integrated into the water vapor retrieval system of the moisture sounder of SSM/T-2.

c) Image Displaying Software Package for MIR Data

A MIR image display system based on the Interactive Data Language (IDL) has been developed in the Microwave Sensor Branch, Laboratory for Hydrospheric Processes, GSFC/NASA. This package is designed with a customized multi-functional widget window application. It displays up to nine channels of brightness temperature in adjustable false colors, corresponding relevant parameters and navigation data as well. The original version was created for use in a personal computer. A modified version is also created for application on a SGI workstation platform.

3. DEVELOPMENT OF WATER VAPOR RETRIEVAL ALGORITHM

a) Water Vapor Retrieval System on a Pressure Coordinate

The previously reported water vapor retrieval algorithm as described in [1] and [2], the first of the report series uses a z-mesh vertical coordinate. Since most of the meteorological prediction model, operational retrieval model, and the routine rawinsonde observation use isobaric surface as the vertical coordinate, it is natural to develop a water vapor retrieval algorithm based on a pressure coordinate system.

An evenly space pressure mesh with increment of 25 mb is adopted. Input parameters and retrieved output parameters are given on mandatory pressure level. Six reference pressure levels, 1000 mb, 850 mb, 700 mb, 500 mb, 300 mb, and 200 mb are chosen as the retrieved output levels (for SSM/T-2, a five channel radiometer, only the first five levels are used.) The forward calculation of the radiative transfer computation is done using a finer pressure mesh ($\Delta p=25$ mb), where the necessary vertical interpolation is done based on a logarithmic pressure variation. This version of the retrieval system basically produces the same result as that by the old system based on z-coordinate.

b) Development of Retrieval Algorithm Based on CRAY-90 Supercomputer Platform

For global water vapor retrieval using spaceborne SSM/T-2 measurements, the speed and throughput of the retrieval system is

of practical importance. The current workstation-based retrieval system has to be revised to efficiently executed in the CRAY super machine. Major revisions include:

- i) The input-output handling.

The bulk of the input radiometric data and model profile data, together with the output data stream should be handled through the use of on-line mass storage disk.

- ii) The use of faster arithmetics.

Since the supercomputer has better accuracy than the workstation, the use of single precision arithmetic manipulation can speed up the execution by a factor of ten times, yet maintains the same level of accuracy as the double precision in the current workstation machine.

- iii) The use of optimization and vectorization.

By restructuring the source code and by the utilization of the featured optimization and vectorized computation in supercomputer, the economy of the CPU time can be achieved.

Current versions of this global retrieval system have implemented the first two revisions and the execution time shows at least ten times faster than that of the workstation version. It will be even more efficient when the last option is implemented.

c) Incorporation of SSM/I Products in Water Vapor Retrieval System

Since SSM/I is on board of the same spacecraft with SSM/T-2 and is capable of detection of total precipitable water, cloud

liquid water and sea surface wind, it is useful to integrate these information into the water vapor retrieval algorithms. Using SSM/I brightness temperatures, these parameters are estimated empirically according to reports [3], [4], and [5]:

Precipitable water PW in kg/m^2 is

$$\begin{aligned} \text{PW} = & 232.89393 - 0.148396 T_{19V} - 1.829125 T_{22V} \\ & - 0.36954 T_{37V} + 0.006193 T_{22V}^2 \end{aligned} \quad (1)$$

Cloud liquid water CLW in kg/m^2 is

$$\begin{aligned} \text{CLW} = & -3.14559 + 1.9595 \times 10^{-2} T_{37V} + 6.0257 \times 10^{-3} T_{19H} \\ & - 4.8803 \times 10^{-3} T_{22V} - 3.0107 \times 10^{-3} T_{85H} \end{aligned} \quad (2)$$

and sea surface wind SSW in ms^{-1} is

$$\begin{aligned} \text{SSW} = & 147.90 + 1.0969 T_{19V} - 0.4555 T_{22V} \\ & - 1.7600 T_{37V} + 0.7860 T_{37H} \end{aligned} \quad (3)$$

with quality flags indicated by the degree of polarization in 37 GHz and 19 GHz.

Where T's are the SSM/I bright temperatures of different frequencies and polarizations, sea surface wind SSW generally roughens ocean surface and increases surface emissivities. An empirical expression is

$$\begin{aligned} E_H &= 1 - R_H + 0.000175 \text{ SSW}^2 \\ E_V &= 1 - R_V + 0.000053 \text{ SSW}^2 \end{aligned} \quad (4)$$

Where E's and R's are the component emissivities and reflectivities of sea water as determined for each microwave frequency using sea surface temperature (SST) and salinity, for example, as reported on [6].

The SSM/I derived precipitable water and cloud liquid water content can be integrated into the SSM/T-2 humidity profiling system as another constraint and cross references.

d) Incorporation of High-resolution Interferometer Sounder (HIS) Products in MIR Water Vapor Retrieval

Since HIS is on board of the same aircraft with MIR and is used to measure a set of meteorological variables, including atmospheric temperature profile, the MIR water vapor retrieval system is modified to input HIS temperature profile instead of other resources. In such a case, proper interpolation of parameters between the HIS grid system and the MIR pressure system should be implemented. This algorithm has been preliminarily tested on the 1995 CAMEX-II data. Although the initial simulation of this implementation does not produce a convergent solution in the MIR water vapor retrieval, it is an excellent strategy to integrate HIS products into the MIR humidity profiling system, as long as these two sensors were flown simultaneously.

4. WATER VAPOR RETRIEVAL DURING TOGA/COARE, 1993 AND CAMEX, 1993 AND 1995

a) Water Vapor Retrieval from SSM/T-2 During TOGA/COARE

The SSM/T-2 on board of spacecraft F-11 of the Defense Meteorological Satellite Project (DMSP) has provided the needed overpass for a humidity profiling over the TOGA/COARE area. Other microwave sensor on board of the same spacecraft, SSM/I, also provides hydrological information such as the integrated precipitable water and cloud liquid water content. For study of the spatial and temporal variation of water vapor during TOGA/COARE, a series of water vapor profile retrievals are performed. The developed retrieval algorithm in pressure coordinate is used. Orbital radiometric data of SSM/T-2 compiled by the Remote Sensing Group of the Texas A&M University, covering from January 14, to February 28, 1993 have been extracted, within the domain of 30°S to 30°N in latitude and 120°E to 180°E in longitude. Generally, within 24 hours, there are two suborbital swaths, one ascending (5:14 PM over the equator) and one descending that will pass through the prescribed domain. Concurrent model output fields of temperature and pressure from European Center for Medium Range Weather Forecast (ECMWF) GCM model are used as the initial input for the retrievals.

Routine radiosonde data from four stations within the domain are collected during the experiment period. Analyses and comparison of time series of the retrievals and radiosondes are

performed in the context of synoptic and climatological changes. Total precipitable water derived from SSM/I and layer precipitable waters derived from TIROS-N Operational Vertical Sounder (TOVS) are cross-referenced and compared. These results will be presented at the 1995 Fall Meeting of the American Geophysical Union (AGU) in San Francisco, USA.

b) Water Vapor Retrievals During CAMEX-I and CAMEX II

The NASA funded experiments, the Convection and Atmospheric Moisture Experiments (CAMEXs) are the multi-disciplinary science efforts following TOGA/COARE. Flight missions loaded with a half dozen of different sensors will provide the necessary measurements to meet various scientific objectives. As usual MIR provided useful information on water vapor and condensed water (cloud) as well.

CAMEX-I was carried out in September and October, 1993, and CAMEX-II in August and September, 1995, over the eastern coast area of the United States. Series of MIR measurements were collected during flight missions. Water vapor retrievals were performed for MIR data of September 30 and October 5, 1993, and for the corresponding SSM/T-2 overpass measurements as well. Due to the cross pattern of the MIR flight path relative to the satellite suborbit, the one-to-one comparison between the respective retrievals was not as good as the previous cases of inter-comparison during TOGA/COARE, namely, February 4 and 10, 1993, where the aircraft flight paths are near parallel to the satellite

suborbits.

Retrievals are also performed for August 25, 1995, of the CAMEX-II. Since the ECMWF data is not available for the input for a long-stretched-path retrieval, experiments were carried out by incorporating the HIS produced temperature and pressure fields. Results indicate solutions are not convergent to the tolerable limit. Near-by rawinsonde profiles are also tested in the retrievals. The improvement is limited to some specific location only. This indicates further investigation is necessary.

5. RECOMMENDATION FOR FUTURE RESEARCH

Significant advancement on the development of water vapor retrieval algorithm has been made. As water vapor is one of the most important meteorological parameters in the control of weather and climate changes, as well as in the linkage of atmospheric energy cycles, the accurate description of water vapor distribution is crucial in the performance of numerical weather predictions. Since ground-based measurements would not provide the needed spatial and temporal coverage, a three-dimensional mapping by a remote sensing technique is a natural choice to overcome this difficulty. So far, reasonable success has been made on the development of microwave humidity profiling methodology, especially over the ocean and under a clear to moderately cloudy sky condition.

To advance sounding technique to handle water vapor retrievals under a variety of meteorological conditions, and over various types of surfaces is the ultimate goal of the task. Therefore, the recommendation for continued development of water vapor retrieval algorithm includes the following:

- i) The handling of different surface types.

Surface emissivity over a calm ocean water can be calculated as described in [6] and can be empirically estimated when there is wind, e.g., equation (4) in Chapter 3. However, surface emissivity over land with different characteristics and moisture content, and over ice or snow with different ages, can vary significantly. Studies of water vapor retrieval over these surfaces should be

carried out using collected MIR data as well as using satellite observation from SSM/T-2 and SSM/I.

ii) The handling of a cloudy atmosphere.

The presence of cloudy conditions alters the physics and complicates the forward radiative transfer and backward inversion calculations. Cloud height and cloud type are also important factors in dictating the observed brightness temperatures. Retrieval under cloudy atmospheres, along with incorporation of visible and infrared techniques into microwave methodology, will help the identification of existing cloud types and cloud height, thus producing more realistic results. Implementation of such techniques with microwave radiometry is even more promising when these different sensors are on board of the same satellite, as the future deployment would be.

iii) The handling of precipitating atmosphere.

Microwaves interact differently with precipitating particles where both absorption and scattering processes should be taken into account. Under such conditions, the radiative transfer process is far more complicated and the computation involved in such simulation is enormously tedious. Nevertheless, a realistic humidity profiling depends on the faithful representation of all relevant physical processes. A full scale three-dimensional treatment of the dynamics and microphysics of cloud and precipitation with all accounted radiative transfer processes would be the ultimate solution for such a problem. However, for practical purposes and before such complete treatment can be

implemented, algorithms with empirical representation for the effect of precipitating atmospheres can be developed. This type of implementation can be done through the use of simultaneous observations from other microwave precipitation sensors (such as SSM/I), and visible or IR sensors as well.

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